

Neutrino oscillation constraints on neutrinoless double-beta decay

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Via P. Giuria 1, I-10125 Torino, Italy***Abstract**

It is shown that, in the framework of the scheme with three-neutrino mixing and a mass hierarchy, the results of neutrino oscillation experiments imply an upper bound of about 10^{-2} eV for the effective Majorana mass in neutrinoless double- β decay. The schemes with four massive neutrinos are also briefly discussed.

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The recent results of the high-precision and high-statistics Super-Kamiokande experiment [1,2] have confirmed the indications in favor of neutrino oscillations [3] obtained in atmospheric [4] and solar [5] neutrino experiments. Here we will discuss the implications of the results of atmospheric and solar neutrino oscillation experiments for neutrinoless double- β decay $((\beta\beta)_{0\nu})$ in the framework of the scheme with three neutrinos and a mass hierarchy, that can accommodate atmospheric and solar neutrino oscillations, and in the framework of the schemes with four massive neutrinos that can accommodate also the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ oscillations observed in the LSND experiment. [6]

The results of atmospheric neutrino experiments can be explained by $\nu_\mu \rightarrow \nu_\tau$ oscillations due to the mass-squared difference [1]

$$\Delta m_{\text{atm}}^2 \sim (1 - 8) \times 10^{-3} \text{ eV}^2. \quad (1)$$

The results of solar neutrino experiments can be explained by $\nu_e \rightarrow \nu_\mu, \nu_\tau$ transitions due to the mass-squared difference

$$\Delta m_{\text{sun}}^2 \sim (0.5 - 10) \times 10^{-10} \text{ eV}^2 \quad (\text{VO}) \quad (2)$$

in the case of vacuum oscillations, or

$$\Delta m_{\text{sun}}^2 \sim (0.4 - 1) \times 10^{-5} \text{ eV}^2 \quad (\text{SMA-MSW}) \quad (3)$$

in the case of small mixing angle MSW transitions, or

$$\Delta m_{\text{sun}}^2 \sim (0.6 - 20) \times 10^{-5} \text{ eV}^2 \quad (\text{LMA-MSW}) \quad (4)$$

in the case of large mixing angle MSW transitions. [7] Hence, atmospheric and solar neutrino data indicate a hierarchy of Δm^2 's: $\Delta m_{\text{sun}}^2 \ll \Delta m_{\text{atm}}^2$. A natural scheme that can accommodate this hierarchy is the one with three neutrinos and a mass hierarchy $m_1 \ll m_2 \ll m_3$, that is predicted by the see-saw mechanism. In this case we have

$$\Delta m_{\text{sun}}^2 = \Delta m_{21}^2 \simeq m_2^2, \quad \Delta m_{\text{atm}}^2 = \Delta m_{31}^2 \simeq m_3^2. \quad (5)$$

In the spirit of the see-saw mechanism, we presume that massive neutrinos are Majorana particles and $(\beta\beta)_{0\nu}$ -decay is allowed. The matrix element of $(\beta\beta)_{0\nu}$ decay is proportional to the effective Majorana neutrino mass

$$|\langle m \rangle| = \left| \sum_k U_{ek}^2 m_k \right|, \quad (6)$$

where U is the mixing matrix that connects the flavor neutrino fields $\nu_{\alpha L}$ ($\alpha = e, \mu, \tau$) to the fields ν_{kL} of neutrinos with masses m_k through the relation $\nu_{\alpha L} = \sum_k U_{\alpha k} \nu_{kL}$. The present experimental upper limit for $|\langle m \rangle|$ is 0.2 eV at 90% CL. [9] The next generation of $(\beta\beta)_{0\nu}$ decay experiments is expected to be sensitive to values of $|\langle m \rangle|$ in the range $10^{-2} - 10^{-1}$ eV.

Since the results of neutrino oscillation experiments allow to constraint only the moduli of the elements U_{ek} of the neutrino mixing matrix, let us consider the upper bound

$$|\langle m \rangle| \leq \sum_k |U_{ek}|^2 m_k \equiv |\langle m \rangle|_{\text{UB}}. \quad (7)$$

In the framework of the scheme with three neutrinos and a mass hierarchy, the contribution of m_1 to $|\langle m \rangle|_{\text{UB}}$ is negligible and the contributions of m_2 and m_3 are given, respectively, by

$$|\langle m \rangle|_{\text{UB2}} \equiv |U_{e2}|^2 m_2 \simeq |U_{e2}|^2 \sqrt{\Delta m_{\text{sun}}^2} \quad (8)$$

$$|\langle m \rangle|_{\text{UB3}} \equiv |U_{e3}|^2 m_3 \simeq |U_{e3}|^2 \sqrt{\Delta m_{\text{atm}}^2}. \quad (9)$$

The parameter $|U_{e2}|^2$ is large in the case of solar vacuum oscillations, is smaller than $1/2$ in the case of large mixing angle MSW transitions and is very small ($|U_{e2}|^2 \lesssim 2 \times 10^{-3}$) in the case of small mixing angle MSW transitions. Taking into account the respective ranges of Δm_{sun}^2 in Eqs.(2)–(4), we have

$$|\langle m \rangle|_{\text{UB2}} \lesssim \begin{cases} 3 \times 10^{-5} \text{ eV} & (\text{VO}), \\ 6 \times 10^{-6} \text{ eV} & (\text{SMA-MSW}), \\ 7 \times 10^{-3} \text{ eV} & (\text{LMA-MSW}). \end{cases} \quad (10)$$

Hence, the contribution of m_2 to the upper bound (7) is small and one expects that the dominant contribution is given by $m_3 \simeq \sqrt{\Delta m_{\text{atm}}^2} \sim (3 - 9) \times 10^{-2} \text{ eV}$. However, as we will show in the following, the value of $|U_{e3}|^2$ is constrained by the results of the atmospheric Super-Kamiokande experiment and by the negative results of the long-baseline reactor $\bar{\nu}_e$ disappearance experiment CHOOZ. [10]

The two-neutrino exclusion plot obtained in the CHOOZ experiments imply that [11] $|U_{e3}|^2 \leq a_e^{\text{CHOOZ}}$ or $|U_{e3}|^2 \geq 1 - a_e^{\text{CHOOZ}}$, with $a_e^{\text{CHOOZ}} = \frac{1}{2} \left(1 - \sqrt{1 - \sin^2 2\vartheta_{\text{CHOOZ}}} \right)$. Here $\sin^2 2\vartheta_{\text{CHOOZ}}$ is the upper value of the two-neutrino mixing parameter $\sin^2 2\vartheta$ obtained from the CHOOZ exclusion curve as a function of $\Delta m^2 = \Delta m_{31}^2 = \Delta m_{\text{atm}}^2$, where Δm^2 is the two-neutrino mass-squared difference. Since the quantity a_e^{CHOOZ} is small for $\Delta m_{\text{atm}}^2 \gtrsim 10^{-3} \text{ eV}^2$, the results of the CHOOZ experiment imply that $|U_{e3}|^2$ is either small or close to one. However, since the survival probability of solar ν_e 's is bigger than $|U_{e3}|^4$, only the range $|U_{e3}|^2 \leq a_e^{\text{CHOOZ}}$ is allowed by the results of solar neutrino experiments. Therefore, the contribution of m_3 to $|\langle m \rangle|_{\text{UB}}$ is bounded by

$$|\langle m \rangle|_{\text{UB3}} \lesssim a_e^{\text{CHOOZ}} \sqrt{\Delta m_{\text{atm}}^2}. \quad (11)$$

Notice that this limit depends on Δm_{atm}^2 both explicitly and implicitly through a_e^{CHOOZ} .

The bound in the $|\langle m \rangle|_{\text{UB3}} - \Delta m_{\text{atm}}^2$ plane obtained from the inequality (11) using the CHOOZ exclusion curve is shown in Fig. 1 by the solid line (the region on the right of this curve is excluded). The dashed straight line in Fig. 1 represents the unitarity bound $|\langle m \rangle|_{\text{UB3}} \leq \sqrt{\Delta m_{\text{atm}}^2}$.

The shadowed and hatched regions in Fig. 1 are allowed [8] by the analysis of the Super-Kamiokande data and the combined analysis of the Super-Kamiokande and CHOOZ data, respectively. One can see that the value of $|\langle m \rangle|_{\text{UB3}}$ is tightly constrained:

$$|\langle m \rangle|_{\text{UB3}} \lesssim 6 \times 10^{-3} \text{ eV}. \quad (12)$$

Therefore, taking into account the inequalities (7), (10) and (12), we conclude that in the scheme with three neutrinos and a mass hierarchy the effective Majorana mass $|\langle m \rangle|$ in $(\beta\beta)_{0\nu}$ -decay is bounded by

$$|\langle m \rangle| \lesssim 10^{-2} \text{ eV}. \quad (13)$$

Let us consider now the two schemes with four-neutrino mixing that can accommodate the results of solar and atmospheric neutrino experiments and the results of the accelerator LSND experiment: [12]

$$(A) \quad \underbrace{m_1 < m_2}_{\text{atm}} \ll \underbrace{m_3 < m_4}_{\text{sun}}, \quad (B) \quad \underbrace{m_1 < m_2}_{\text{sun}} \ll \underbrace{m_3 < m_4}_{\text{atm}}. \quad (14)$$

LSND

These two spectra are characterized by the presence of two couples of close masses separated by a gap of about 1 eV which provides the mass-squared difference $\Delta m_{\text{LSND}}^2 = \Delta m_{41}^2$ responsible of the oscillations observed in the LSND experiment. In the scheme A $\Delta m_{\text{atm}}^2 = \Delta m_{21}^2$ and $\Delta m_{\text{sun}}^2 = \Delta m_{43}^2$, whereas in scheme B $\Delta m_{\text{atm}}^2 = \Delta m_{43}^2$ and $\Delta m_{\text{sun}}^2 = \Delta m_{21}^2$.

It has been shown [12] that the results of the short-baseline $\bar{\nu}_e$ disappearance experiment Bugey, [13] in which no indication in favor of neutrino oscillations was found, imply that the mixing of ν_e with the two “heavy” neutrinos ν_3 and ν_4 is large in scheme A and small in scheme B. Therefore, if scheme A is realized in nature the effective Majorana mass in $(\beta\beta)_{0\nu}$ decay can be as large as $m_3 \simeq m_4 \simeq \sqrt{\Delta m_{\text{LSND}}^2} \simeq 0.5 - 1.2 \text{ eV}$. On the other hand, in scheme B $(\beta\beta)_{0\nu}$ decay is strongly suppressed. Indeed, the contribution of m_2 to the upper bound (7) is limited by Eq.(10) and the contribution of m_3 and m_4 , $|\langle m \rangle|_{\text{UB34}} \simeq (|U_{e3}|^2 + |U_{e4}|^2) \sqrt{\Delta m_{\text{LSND}}^2}$, is limited by the inequality

$$|\langle m \rangle|_{\text{UB34}} \lesssim a_e^{\text{Bugey}} \sqrt{\Delta m_{\text{LSND}}^2}, \quad (15)$$

where a_e^{Bugey} is given by the exclusion curve of the Bugey experiment. The numerical value of the upper bound (15) is depicted in Fig. 2 by the solid line. The dashed straight line in Fig. 2 represents the unitarity bound $|\langle m \rangle|_{\text{UB34}} \leq \sqrt{\Delta m_{\text{LSND}}^2}$ and the shadowed region indicates the interval of Δm_{LSND}^2 allowed at 90% CL by the results of the LSND experiment: $0.22 \text{ eV}^2 \leq \Delta m_{\text{LSND}}^2 \leq 1.56 \text{ eV}^2$. From Fig. 2 one can see that $|\langle m \rangle|_{\text{UB34}} \lesssim 2 \times 10^{-2} \text{ eV}$. Therefore, in scheme B we have the upper bound

$$|\langle m \rangle| \lesssim 2 \times 10^{-2} \text{ eV}. \quad (16)$$

In conclusion, the results of the analysis of neutrino oscillation data show that the effective Majorana mass $|\langle m \rangle|$ in neutrinoless double- β decay is smaller than about 10^{-2} eV in the scheme with mixing of three neutrinos and a mass hierarchy, is smaller than about $2 \times 10^{-2} \text{ eV}$ in the four-neutrino mixing scheme B, whereas it can be as large as $\sqrt{\Delta m_{\text{LSND}}^2} \simeq 0.5 - 1.2 \text{ eV}$ in the four-neutrino mixing scheme A.

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FIGURES

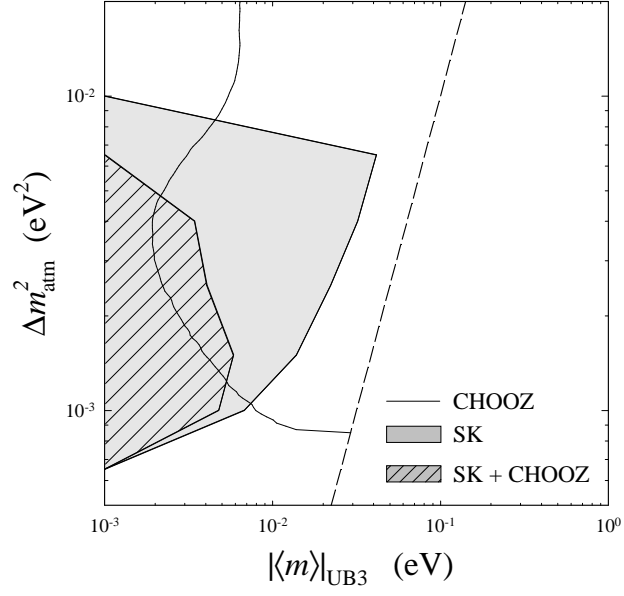


FIG. 1.

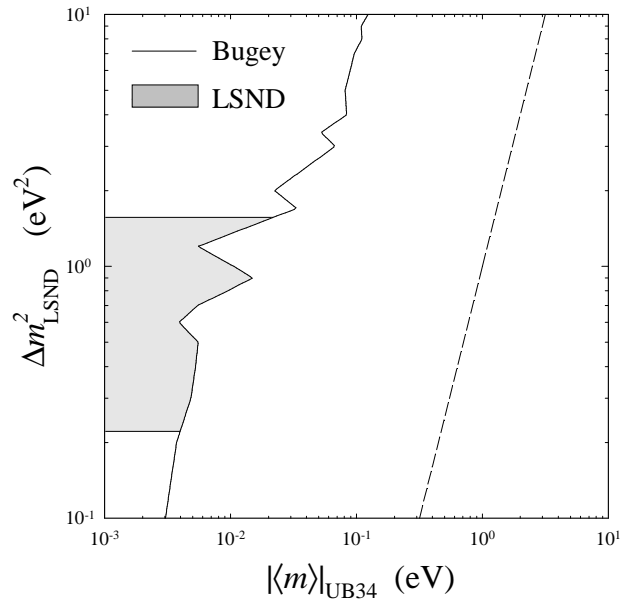


FIG. 2.